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Application of Autonomous Agent Concepts to Robotic Fleet Dynamics

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ABSTRACT

The fighting effectiveness and force projection capability of the U. S. Army's Future Force will be significantly increased with deployment of Future Combat Systems (FCS), which include significant numbers of unmanned vehicles and robotic systems to conduct missions ranging from reconnaissance to re-supply to direct assault. Successful application of these robotic systems requires new levels of objective-based autonomous behavior in mixed-fleet scenarios. To meet these requirements for robotic fleet dynamics, designers and integrators should apply autonomous agent concepts and recent research results. As the concepts are demonstrated and improved in challenging environments, they can be further extended to additional applications for the military as well as new ones in the commercial/civil sector.

This paper defines the autonomous agent concept and describes its important elements, including goal seeking, resourcefulness, and the optional ability for agents to transfer themselves or clone themselves among physical hosts. Fleet dynamics are discussed as applicable to robot coordination in group maneuvers, complex missions, and rapidly changing conditions and constraints. Multiple aspects of fleet dynamics are considered including distinction of multiple roles, transfer of roles under triggering conditions, and the impact of various strategies of information sharing, whether local, near neighbor, or wide-area broadcast, on fleet performance, robustness, and adaptability.

This paper includes a review of promising research results for autonomous agent concepts in academic and military settings and identifies specific methods that appear useful for application to robotic and mixed fleets.

Several military and commercial/civil applications are identified for which the autonomous agent concept is especially useful. Technology gaps where additional research and development is justified to overcome current limitations are highlighted.

The significant risks and challenges for application of autonomous agents in robotic and mixed fleets are listed, including human safety, security, manageability, visualization, integration with command-and-control systems, and in-field upgrades.

Finally, current research and development activities for autonomous agents and robotic fleet dynamics are described along with opportunities to accelerate future research results.

INTRODUCTION

The fighting effectiveness and force projection capability of the U. S. Army's Future Force will be significantly increased with deployment of Future Combat Systems (FCS), which include significant numbers of unmanned vehicles and robotic systems to conduct missions ranging from reconnaissance to re-supply to direct assault. The Army's future force projection scenario estimates one third of the fighting force to be unmanned, with up to four unmanned ground vehicles (UGVs) directed by one soldier.[1] The projected force will include a mixed composition of manned and unmanned vehicle types.

Successful application of these robotic systems requires new levels of objective-based autonomous behavior in mixed-fleet scenarios. In the envisioned mission scenarios, unmanned vehicles may need to:

- Support/conduct military missions ranging from peace-keeping to full combat
- Coordinate combined effects of multiple robots, manned systems, and soldiers, even if individual elements are redirected, incapacitated, or encounter unexpected conditions
- Travel independently or in formation

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14. ABSTRACT

The fighting effectiveness and force projection capability of the U. S. Army?s Future Force will be significantly increased with deployment of Future Combat Systems (FCS), which include significant numbers of unmanned vehicles and robotic systems to conduct missions ranging from reconnaissance to re-supply to direct assault. Successful application of these robotic systems requires new levels of objective-based autonomous behavior in mixed-fleet scenarios. To meet these requirements for robotic fleet dynamics, designers and integrators should apply autonomous agent concepts and recent research results. As the concepts are demonstrated and improved in challenging environments, they can be further extended to additional applications for the military as well as new ones in the commercial/civil sector. This paper defines the autonomous agent concept and describes its important elements, including goal seeking, resourcefulness, and the optional ability for agents to transfer themselves or clone themselves among physical hosts. Fleet dynamics are discussed as applicable to robot coordination in group maneuvers, complex missions, and rapidly changing conditions and constraints. Multiple aspects of fleet dynamics are considered including distinction of multiple roles, transfer of roles under triggering conditions, and the impact of various strategies of information sharing, whether local, near neighbor, or wide-area broadcast, on fleet performance, robustness, and adaptability. This paper includes a review of promising research results for autonomous agent concepts in academic and military settings and identifies specific methods that appear useful for application to robotic and mixed fleets. Several military and commercial/civil applications are identified for which the autonomous agent concept is especially useful. Technology gaps where additional research and development is justified to overcome current limitations are highlighted. The significant risks and challenges for application of autonomous agents in robotic and mixed fleets are listed, including human safety, security, manageability, visualization, integration with command-and-control systems, and in-field upgrades. Finally, current research and development activities for autonomous agents and robotic fleet dynamics are described along with opportunities to accelerate future research results.

15. SUBJECT TERMS

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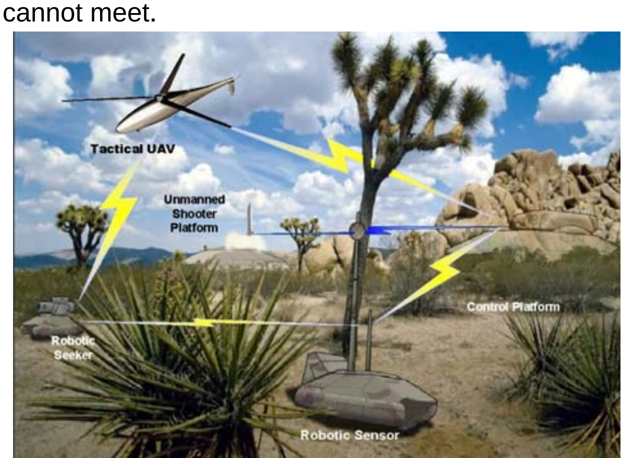
- Cross difficult terrain and avoid obstacles and threats, whether physical or military
- Conduct threat analysis and take appropriate counter-measures
- Minimize unintended damage to people, payload, other equipment, and surroundings
- Manage energy expenditure and recharge/refuel if needed
- Minimize signature to hostile forces
- Employ sensors, actuators, or weapons in the correct circumstances and situations
- Pick up or drop payloads as intended by commanders

This challenging list of requirements cannot be met with conventional approaches. The recent disappointing results of the 2004 DARPA "Grand Challenge" race for unmanned vehicles in the US Southwest highlights the difficulty of meeting even basic mission objectives in rugged terrain. No UGV entered in the challenge completed more than 7 miles of the 200 mile course.[2] Many entrants failed to have flexible, adaptable or alternative approaches when encountering obstacles or ambiguous sensor data. Other vehicles did not have sufficient algorithms to avoid risks that could impair themselves. It is probably true that many of the design teams failed by over-relying on one or two major feedback and control strategies that turned out to be overly simplistic, such as relying on GPS-based navigation alone. More sophisticated approaches will be needed for successful completion of any long-range overland mission, whether a DARPA challenge race or a mission in an FCS unit of action.

The success of Future Combat Systems relies heavily on unmanned ground and air vehicles with some level of autonomous control that exceeds direct "man-in-the-loop" real-time remote guidance. Robotic systems will need to have very powerful and diverse approaches to meet mission objectives independently while simultaneously addressing the requirements and constraints listed above. A common term for this type of loosely-directed, empowered actor is an "autonomous agent." There is a growing body of research on how autonomous agents can be implemented and then coordinated to achieve goals that individual agents cannot meet.



This paper will describe various autonomous agent approaches and review the observed effectiveness seen in experiments conducted by academic and military researchers.

Once practical methods are developed to implement cooperative teams of robots, several commercial homeland defense applications become feasible. One application is security patrol of large and remote areas. There are tremendous challenges patrolling borders and defending sensitive installations. Fleets of robots can cooperate to patrol these areas around the clock and with unpredictable patterns. A second application is search and rescue missions following disasters such as fire, flood, and earthquakes. Teams of robots can be dispersed to detect survivors and lead human rescuers to their location. The rescue robots may be able also to provide emergency supplies to victims before human first responders can arrive. The "ITR: Multi-Robot Emergency Response" program funded by the National Science Foundation at the University of Minnesota led by the Principle Investigator Nikolaos Papanikolopoulos has pioneered the demonstration of such a search and rescue system.[3] There are many potential applications in agriculture and forestry. Groups of robots can monitor crops, identify and manage pests, harvest produce, and apply fertilizers and treatments. In mining, robotic agents can cooperate to identify minerals, set explosive charges, burrow through rock, and transfer ore to conveyor systems. As the safety and flexibility of these systems are proven, autonomous transportation agents may begin to join streets, roads and highways to haul cargo and taxi passengers. The potential applications appear limitless, but the platforms and algorithms must be incrementally improved, capturing successful technology and approaches in core systems and facilitating further experimentation and development.

AUTONOMOUS AGENTS

DEFINITIONS

According to Stan Franklin and Art Graesser, "an autonomous agent is a system situated within and a part of an environment that senses that environment and acts on it, over time, in pursuit of its own agenda and so as to effect what it senses in the future." Therefore, an unmanned vehicle that is operated through continuous telemetry and remote control will not be considered an autonomous agent. This paper will focus on ground-based autonomous systems and will not specifically address unmanned aerial vehicles (UAVs) nor smart bombs and guided missiles, although these systems may benefit from certain autonomous agent concepts as well.

To be a fully autonomous agent, a robot must be goal seeking without detailed mission-specific pre-programming. While some robotic systems perform a highly detailed but fixed sequence of actions, which is

useful in contexts such as manufacturing, such systems will not be feasible for deployment in FCS units of action. Goal-seeking means the robot is capable of planning and enacting a course of action that results in accomplishment of a defined goal in an acceptable manner, where the acceptability may be defined in terms of constraints such as time, accuracy, and undesirable side-effects. Accomplishing non-trivial goals in complex environments will require autonomous agents that are able to determine a sequence of sub-goals that lead to the overall goal without generating unacceptable risk or side effects. The autonomous agent will also need to exhibit adaptation and learning so performance increases throughout a mission. Finally, the robot must be able to determine when the goal is met.

The algorithms that define an agent's behavior can be executed inside the robot or a host that has a suitable communications link with the robot. For command and control purposes, it is very helpful if the current goal or mission parameters and constraints for each agent can be revised during its mission, although for security and robustness it is risky to depend 100% on remote communication.

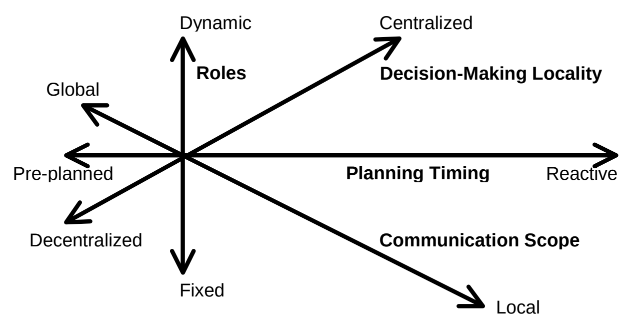
Practical autonomous robots will need to be resourceful, which means they can determine multiple potential options for a needed action and attempt them in turn based on observed progress. A resourceful robot will include a high level supervisory and learning system that constantly evaluates differences between observed and expected results of actions, effectiveness of recent actions, and the likely result of each alternative action before attempting the next action and then utilizes learning strategies to favor recent options that proved more successful during evaluation. In fleet scenarios, a wide variety of movement and task performance options may be possible for the collection of robots and manned systems, so the collective behavior can more resourceful than the individual actions. Whether this resourcefulness comes from a single sophisticated agent or from competition among many simpler agents, it provides greater much greater flexibility and fault-tolerance.

Military objectives, and many commercial ones, require coordinated actions of many agents whether human or software-driven. A fleet of vehicles, both manned and unmanned, may need to traverse a complex course. Hazards and obstacles such as bridges, cliffs, and enemy fortifications may require changing formations and temporary diversions. Different members in a maneuver unit may have different roles to play, and these roles can vary with time as members are added, diverted, or incapacitated. Autonomous agents within the fleet will need to be able to react to changing conditions and mission parameters, and adjust their roles accordingly. The management of roles might be accomplished by "moving" autonomous agent state information among robots, or by transmitting updates on objectives and constraints to the agents.

AGENT-BASED APPROACHES

There are many agent-based approaches to managing fleet dynamics that can be classified according to different aspects. No single approach is likely to be successful under all missions and UGV task types. In this section, we describe the range of options along different solution approach axes.

One of the most well-researched solution axes is the centralized versus decentralized decision-making locality. With perfect fleet-wide data, a centralized planning agent can analyze the current situation, plan individual actions, transmit detailed instructions to subservient agents in the fleet and can monitor progress. This approach concentrates the majority of computing requirements at a single node and demands high-bandwidth, low latency communication with all robots at all times. The centralized planning approach perhaps allows the best opportunities for fleet-wide optimization of performance at a cost in robustness: a single-point failure of the central planning agent can immobilize the fleet.



Autonomous Agent-Based Solution Approach Axes

The opposite approach from the centralized planning agent is the decentralized planning agents approach. In this approach, each agent assesses its own ability to contribute to the overall mission and objectives, plans its actions, and then coordinates and cooperates more or less with other agents throughout the mission. This approach can be very fault-tolerant and robust to changing conditions and can reduce the need for wide-area communications. However, the collection of agents may not collectively optimize performance, and might, in fact, miss key objectives (the "it slipped through the cracks" syndrome).

An extreme form of the decentralized planning approach is the so-called "Ant System" approach, where a swarm of agents, virtual or potentially real, explore a solution space in a combination of random and directed behavior.[4] The premise is that one or more agents will happen upon a good solution, much like a wandering ant may find a good source of food. Just as this ant can provide a trail for later ants to follow, the lead agent can direct other agents, who in turn may find a more optimal path. The path in the solution space, virtual or real, can represent any set of actions to be performed by the robot. Therefore, in the virtual scenario, each physical robot may compute a swarm of simulated agents to

explore potential options for each action making up a mission. The “winning” simulated agent then gains control of the robot (in some sense) for that action.

A second agent-based solution approach axis is fixed versus dynamic roles. The extreme form of fixed-role is where each physical robot is designed for a fixed purpose with a finite set of functions and is controlled by a fixed agent optimized for that purpose. The current Future Combat Systems architecture contains several fixed-purpose unmanned robotic systems, such as the cargo transporting “mule”. For a given set of resources, a fixed-role agent can be developed for higher performance in the pre-defined role, at the cost of flexibility in mission planning and robustness to changing conditions experienced in the mission. Agents that can perform dynamically changing roles offer greater flexibility for planning and can handle a wider range of unexpected situations. At current levels of technology, fully autonomous vehicles are more easily implemented with a fixed-role approach. Human agents can be very dynamic in changing roles and managing multiple roles. Semi-autonomous, human-guided agents provide intermediate flexibility to change roles dynamically.

A third agent-based solution approach axis is a pre-planned versus reactive planning timing approach. A fully pre-planned approach requires full understanding of the operating environment and future conditions. Then each action and movement of each robot in the fleet can be planned and communicated ahead of time. During the mission the performance of each action and movement can be tracked and compared to the plan. If the performance deviates too far from the plan or the observed conditions do not fit the expectations, the agents executing the plan can abort. While this approach works well in highly-controlled situations such as manufacturing, real-world fleet missions are performed in environments that are not well defined and continuously face changing conditions. The results of the DARPA Grand Challenge as discussed above shows the folly of relying too heavily on “blind” navigation within a constrained pre-planned route. A reactive approach minimizes the planning activity and continuously evaluates the best action at the moment that takes the robot and/or fleet toward the mission objectives. While a completely reactive agent may find itself “stuck” in a localized set of constraints, it is possible to combine pre-planning and reactive behaviors to balance robustness to unexpected conditions with ability to maximize performance.

A fourth agent-based solution approach axis is global versus local communications scope. Global communications presumes that each individual agent in the fleet can communicate with any and all agents for the purposes of information sharing, command issuing, and collective decision-making. While useful for optimizing performance, global communications can become prohibitively expensive to implement and can introduce detection and targeting risk in military applications. The local communications approach limits communication to near-neighbors, or in extreme cases, to the individual robot itself (where a robot only relies on passive sensing of other robots to coordinate behavior). Local communication reduces implementation cost and makes the robots less detectable by enemies, but provides far less information for coordinating complex tasks and wide-area maneuvers. Hybrid approaches include a hierarchy of communication, where local communication is more frequent and covert, but wider-area communication still occurs to help facilitate dispensation of objectives and critical real-time observations. Another approach inspired by modern networks such as the Internet uses multi-hop forwarding to accomplish global communications using a loosely organized series of local communication transactions. The modern battlefield and new commercial applications will exploit this robust and flexible kind of communications.

Some combinations of approaches tend to go together. Examples:

- Central-planning, pre-planned, fixed-role, with global communications
- Decentralized-planning, reactive, dynamic-role, with local communications (“Swarm robotics”)

Future applications, including military robotic fleets and new commercial applications, will likely require a blended mixture of approaches that will need to be managed dynamically. In a certain mission, a UGV may be a fully autonomous agent for one task, a semi-autonomous human-guided agent in another task, and be remotely driven by a human agent in a third task. It becomes clear that advances in planning and control agents for fleet dynamics will depend on the existence of well-defined systems architecture and dynamic interoperability methods.

RECENT RESEARCH AND DEVELOPMENT ACTIVITIES

There are many recent and current research efforts for autonomous agents that address the challenges of multi-robot coordination and fleet dynamics. Belta and Kumar of the University of Pennsylvania studied the application of advanced geometric mathematical techniques for motion planning and control of multi-robot systems.[5] Simulation and physical testing of groups of robots yielded good performance on tunnel-passing and area-coverage tasks. Carpin and Parker developed a decentralized leader-follower approach for heterogeneous groups of robots.[6] The approach, based on anonymous broadcasts, was shown to be fully scalable for team size and handles communication failures. The approach was demonstrated in both indoor and outdoor environments.

Lynne Parker previous research included development of a learning adaptation model called L-ALLIANCE that includes behavior monitors and characteristics of autonomous agents termed impatience and

acquiescence. [7] The impatience characteristic allows an agent to take over a tasks not being performed well by another, which can acquiesce to the (hopefully) more effective agent. The monitor can help tune the behaviors for successful partitioning of assignments.

These interesting approaches are often physically demonstrated with ad-hoc robotic platforms that require much engineering support effort, often performed by graduate students who are not primarily involved with design and implementation of sensing devices, actuator drive systems, and other technical disciplines. A solution to this situation is discussed later in this paper.

The Army, with support of other government agencies is researching sophisticated sensing, planning, and feedback-based control systems for autonomous agents. The four Dimensional (space and time), Real-time, Control System (4D/RCS) is a National Institute of Standards and Technology (NIST) developed reference architecture and engineering methodology that supports a domain independent approach to goal-directed sensory-interactive adaptable behavior. 4D/RCS integrates high-level cognitive reasoning with low-level perception and feedback control in a modular, well structured, and theoretically grounded methodology. 4D/RCS was originally developed for the Army's Demo III program. It is currently being applied to autonomous intelligent vehicle control under TARDEC's Vetronics Technology Integration program, ARL's Semi-Autonomous Robotics Technology Insertion (SARTI) and the Collaborative Technology Alliance (CTA) programs, as well as for the DARPA Multiple Autonomous Robot Software (MARS) program.

The 4D/RCS architecture is particularly well suited to support adaptability and flexibility in an unstructured, dynamic, tactical environment. It is modular and hierarchically structured with multiple sensory feedback loops closed at every level. This permits rapid response to changes in the environment within the context of high-level goals and objectives. At the lowest (Servo) level, 4D/RCS closes actuator feedback control loops within milliseconds. At successively higher levels, 4D/RCS responds to more complex situations with reactive behaviors and real-time replanning. At each level, 4D/RCS combines perceived information from sensors with a priori knowledge in the context of operational orders, changing priorities, and rules of engagement provided by a human commander. At each level, plans are constantly recomputed and reevaluated at a range and resolution in space and time that is appropriate to the duties and responsibilities assigned to that level. At each level, reactive behaviors are integrated with real-time planning to enable sensor data to modify and revise plans in real-time so that behavior is appropriate to overall goals in a dynamic and uncertain environment. This enables reactive behavior that is both rapid and sophisticated. At the section level and above, 4D/RCS supports collaboration between multiple heterogeneous manned and unmanned vehicles (including combinations of air and ground vehicles) in coordinated tactical behaviors. 4D/RCS also permits dynamic reconfiguration of the chain of command, so that vehicles can be reassigned and operational units can be reconfigured on the fly as required to respond to tactical situations.

RESEARCH NEEDS AND OPPORTUNITIES

When surveying research activity, one recognizes much "reinventing the wheel" to implement basic sensor, communication, and control systems for robotic research platforms. Each research group tends to devote a very large percentage of time and money on these engineering issues and has limited resources remaining to experiment with and refine the agent algorithms. While this tendency is natural in academic environments where there are educational benefits to junior researchers, this misallocation of resources is ultimately wasteful and inhibits progress. Government and commercial organizations will demand consistent progress and improvements.

A better approach includes shared use of a consistent hardware integration platform and robotic operating system that provides:

- A 'system of systems' framework to integrate various sensor, actuator, control, and communication systems, providing software Application Programming Interfaces (APIs) and pre-defined hardware integration approaches (e.g. standardized signal routing, connectors, etc.)
- Standardized communications channels (wireless and/or wired) internal to each robot and external to other robots and humans
- Defined types of computer processing modules for various purposes that easily integrate and interoperate; specific types may include:
    - Data acquisition and signal conditioning modules for sensors
    - Diagnostic and prognostic modules for analysis of system "health"
    - Motor and other actuator control modules
    - High-bandwidth signal processing and pattern recognition modules for images and audio
    - High-level planning, coordination, and adaptation units
- Software architecture to host and manage agent-based behavior algorithms in addition to managing computer resources (memory, task processing time) and hardware devices
- Dynamic ability to share sensor data feeds between robots and with human observers
- Dynamic ability to quickly switch control of each robot from autonomous agent system to human agent "remote driver" and back, including potential support for:
    - Human-in-the-loop remote pilot
    - Voice or gesture command
    - FBCB2 and MTS-type digitized command and control systems

- Dynamic management of autonomous agents, so different types of agent algorithms can be activated and utilized as warranted by mission and conditions
- Mission simulation/rehearsal and training operation modes
- System development and test support tools to help human researchers and development engineers

With common integration platforms in place for autonomous systems, researchers and developers will be free to truly innovate at the algorithm, planning, and control strategies level. The integration platform will help developers rapidly explore solutions for FCS mission profiles and commercial applications. More sophisticated approaches to realistic test cases such as the DARPA Grand Challenge for autonomous vehicles will be implemented and improved. It may be useful for entries to future autonomous robot competitions to be built from a such a common platform, so the unique value of various planning and coordination algorithms or specialized sensing systems can be more easily determined and evaluated for future research investments.

The Department of Defense's Joint Technical Architecture-Army (JTA-A) and Joint Architecture for Unmanned Systems (JAUS) [8] are two examples of a standardization and communization effort for electronics systems that are especially important for guiding developmental programs resulting in deployment. There is a great opportunity to bridge the research activities in universities and government laboratories to full development programs with electronics integration platform technologies that are compatible with the purpose and requirements of the Army's joint technical architectures.

CONCLUSION

The development of a standardized software architecture that supports software modularity, hardware independency and autonomous agent integration has long been a thrust of Army Science and Technology programs as well as a focus of current weapon system architecture standards including Joint Technical Architecture-Army (JTA-A), Joint Architecture for Unmanned Systems (JAUS), Vetronics Reference Architecture, etc. The Future Force, with Future Combat System and Land Warrior Advanced Capability at the forefront, places an emphasis on the use of unmanned vehicles in conjunction with manned or other unmanned systems, and elevates the already critical need for real-time situational awareness, intelligent and adaptable robotic behaviors and teaming, information sharing, global force planning, survivability and dynamic communication networks. Meeting these objectives will require unmanned systems to apply much more sophisticated autonomous agent algorithms and communications capabilities. The autonomous agent concepts discussed in this paper can be applied to permit the automation of both driving and mission functions for current force manned systems, thereby greatly reducing soldier workload. In addition, optimization of agent based approaches will facilitate fully autonomous agents in the Future Force through the enabling of electronics integration platforms, which enable software reuse, leverage of unmanned system control modules, and support hardware independency. The Army and industry predict this approach will greatly accelerate development and fielding of autonomous vehicles meeting FCS needs while providing a foundation for commercial fleet applications, Homeland Defense technologies and space exploration exploits.

The Army's new approach to support research and development of autonomous agents is to provide developers a basic platform that provides fundamental mobility, computing, and communication functions. On this platform, researchers and developers can add higher level sensing, analysis, planning, execution, and learning capabilities. The Army anticipates that the new approach will accelerate technology development and readiness levels and help meet challenging objectives.

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